Preprint
UCRL-JC-144298

Improving 351 –nm Damage Performance of Large-Aperture Fused Silica and DKDP Optics

A.K. Burnham, L. Hackel, P. Wegner, T. Parham, L. Hrubesh, B. Penetrante, P. Whitman, S. Demos, J. Menapace, M. Runkel, M. Fluss, M. Feit, M. Key, T. Biesiada

This article was submitted to
LST Technology Review, Livermore, CA, March 22-23, 2001

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

January 7, 2002

Improving 351-nm damage performance of large-aperture fused silica and DKDP optics

A. K. Burnham,* L. Hackel, P. Wegner, T. Parham, L. Hrubesh, B. Penetrante, P. Whitman, S. Demos, J. Menapace, M. Runkel, M. Fluss, M. Feit, M. Key, T. Biesiada

University of California, Lawrence Livermore National Laboratory
P. O. Box 808, L-592, Livermore, CA 94551

ABSTRACT

A program to identify and eliminate the causes of UV laser-induced damage and growth in fused silica and DKDP has developed methods to extend optics lifetimes for large-aperture, high-peak-power, UV lasers such as the National Ignition Facility (NIF). Issues included polish-related surface damage initiation and growth on fused silica and DKDP, bulk inclusions in fused silica, pinpoint bulk damage in DKDP, and UV-induced surface degradation in fused silica and DKDP in a vacuum. Approaches included an understanding of the mechanism of the damage, incremental improvements to existing fabrication technology, and feasibility studies of non-traditional fabrication technologies. Status and success of these various approaches are reviewed. Improvements were made in reducing surface damage initiation and eliminating growth for fused silica by improved polishing and post-processing steps, and improved analytical techniques are providing insights into mechanisms of DKDP damage. The NIF final optics hardware has been designed to enable easy retrieval, surface-damage mitigation, and recycling of optics.

Keywords: fused silica, DKDP, laser damage, laser damage mitigation, laser damage growth

1. INTRODUCTION

The National Ignition Facility (NIF), currently under construction, will contain 7360 large optics of 40-cm size or larger.[1] The laser consists of 192 beams with a nominal energy of 3 MJ at 1053 nm (1ω) and 1.8 MJ at 351 nm (3ω). The conversion of laser light to 351 nm is needed for improved coupling to the laser targets in order for the NIF to achieve its primary mission within the Stockpile Stewardship program. A schematic diagram of the final optics assembly, in which frequency conversion, beam smoothing, and focusing occur, is given in Figure 1. Achieving the desired lifetime of the 3ω optics has been challenging, and their lifetime can have a significant impact on the operating costs of the facility. Consequently, there has been a considerable effort over the past few years to improve the UV optics performance.

UV optics are made of deuterated potassium dihydrogen phosphate (DKDP), which generates the 351-nm light, and fused silica, from which the focus lens, beam sampling grating, and debris shield are made. Laser-induced damage can occur from defects in both the bulk and the surface of the material. A summary of the different types of damage is given in Table 1. Note that there are similarities and differences between the damage characteristics of DKDP and fused silica. For example, both fused silica and DKDP are susceptible to surface damage that grows exponentially with the number of shots at constant fluence.[2] In contrast, bulk damage in crystals occurs as numerous pinpoints that do not grow significantly,[3] while bulk damage in fused silica is rare but causes growable rear-surface damage from beam modulation when it does occur.[4] Both fused silica and DKDP are susceptible to surface degradation in a vacuum, but the details are different.[5,6]

This paper describes the efforts over the past two years to solve these laser-induced damage problems for the NIF laser. These efforts have been extremely successful. The solutions fall into three categories: (1) reduce or eliminate bulk damage by improved material synthesis, (2) eliminate surface degradation by increasing the operating pressure to 10 Torr, and (3) control surface crater damage through a combination of better finishing processes and a pre-initiate/mitigate sequence. The surface damage mitigation methods can also be applied to optics retrieved from service before the surface damage craters

* Correspondence: Email: burnham1@llnl.gov; Telephone: 925-422-7304; Fax: 925-422-5099

become too large. The overall strategy is portrayed graphically in Figure 2. The technology developments summarized here should be widely applicable to large-aperture high-peak-power lasers.

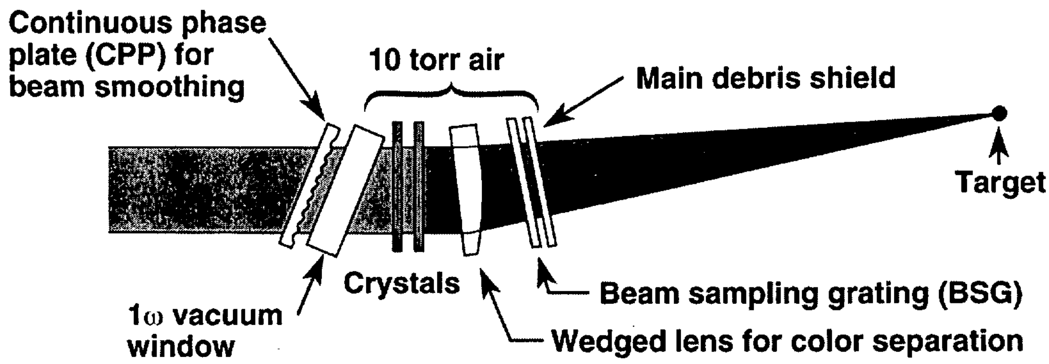


Figure 1. Schematic diagram of the final optics assembly used in the National Ignition Facility to convert infrared laser light (1053 nm) to UV laser light (351 nm).

Table 1. Summary of types of damage for fused silica and crystal optics typically used in large-aperture, high-peak-power lasers such as the National Ignition Facility.

	DKDP	Fused Silica
Bulk Damage	• Up to a few thousand pinpoints/mm^3 • nonisotropic	• Tens of bulk damage sites per optic for refractory-furnace based material
Surface Damage	• Up to a few near-surface bulk damage pinpoints/cm^2 • <50 surface damage sites of size 50-100 μm; possibly related to imbedded particles from fabrication* • Induced roughness and absorption upon UV vacuum exposure	• Many sub-μm pinpoints from residual polishing material (gray haze) • 20-100 μm damage initiation craters, with the number depending on fluence* • Tens of rear-surface damage sites caused by bulk inclusions and lenslets* • Induced absorption upon UV vacuum exposure

*Susceptible to growth at NIF fluences

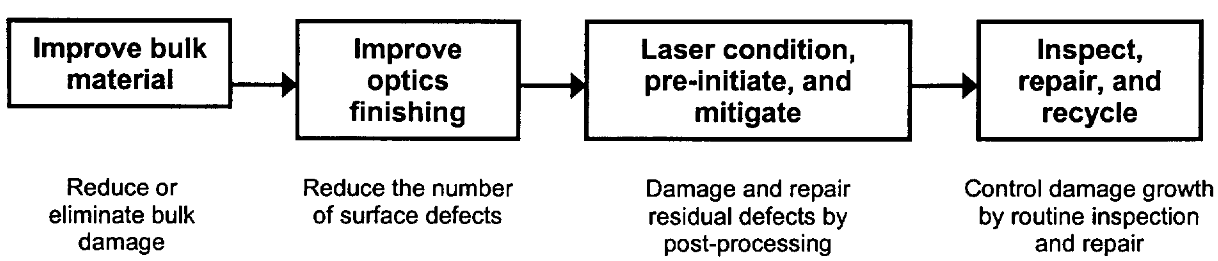


Figure 2. General scheme for improving damage performance and reducing optics replacement costs.

2. BASIC DAMAGE STATISTICS

Laser damage probability or density depends on fluence F according to some function d(F). A large aperture beam consists of a distribution of fluences (i.e., contrast) across the beam, and the damage probability or density $D(<F>)$ at any given area is given by convolving the damage function d(F) with the fluence probability function p(F):[7]

$$D(<F>) = \int_0^\infty p(<F>,F)\, d(F)\, dF \qquad (1)$$

where $<F>$ is the most probable fluence. The operational beam is assumed a nominal flattop with intensity fluctuations described by a Rician distribution.[8] The resulting hot spots are assumed to move randomly shot to shot. The single shot Rician probability distribution p(f) is given by

$$p(F,<F>,c) = (1/2\sigma^2)\exp[-(F+<F>-2\sigma^2)/2\sigma^2]*I_0\{(F/\sigma^2)[(F/<F>)*(1-2\sigma^2/<F>]^{0.5}\} \qquad (2)$$

where $<F>$ is the mean fluence, σ the standard deviation of the noisy field amplitude, and I_0 is a Bessel function of the second kind. The intensity contrast c is twice σ. Although the functional form looks complicated, the distribution profiles of interest are very nearly Gaussian for beam contrast up to 20%. The contrast in the beam can move spatially from shot to shot, meaning that any given location can see a different fluence for each shot at constant average beam fluence. For a randomly migrating fluence, the distribution of maximum fluences at each location after n shots is given by

$$p_m(F) = n\, p(F) * [\int_0^F p(F)dF]^{n-1} \qquad (3)$$

Plots of the maximum fluence distributions for a Rician distribution after 1 to 1000 shots is given in Figure 3. Note that after many shots for this assumption, most locations have been exposed to a fluence at the high end of the single shot distribution. The cumulative damage probability after n shots is found by replacing p(F) by $p_m(F)$ in Eq (1).

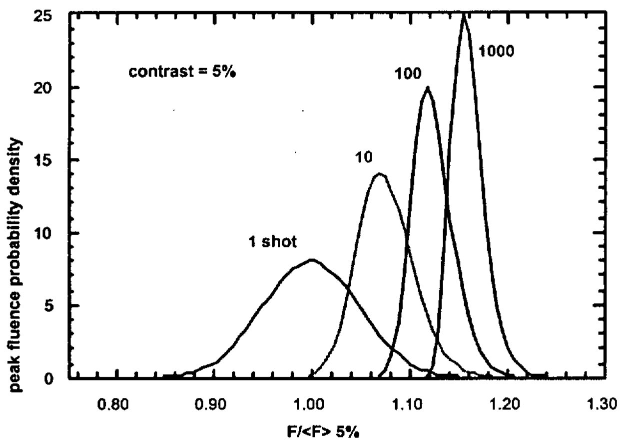


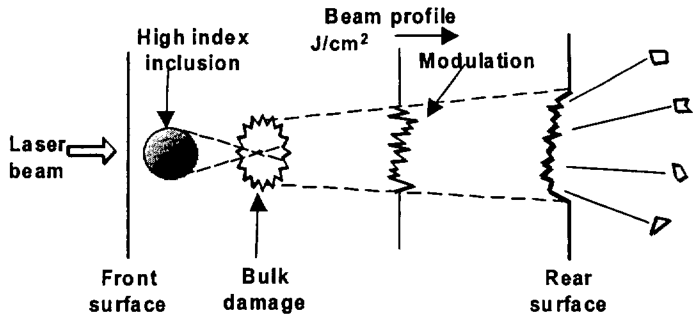
Figure 3. Probability distribution of maximum fluence after 1, 10, 100 and 1000 shots for 5% randomly migrating contrast.

3. IMPROVING BULK MATERIAL

3.1 Fused silica

Fused quartz and fused silica are available in a wide range of quality, depending on their method of manufacture. Fused quartz is not suitable for high-performance optics due to the large number of inclusions that lead to bulk damage. Fused silica, formed by oxidizing chemical precursors and collecting the soot on a boule, is much better but still comes in a range of quality depending on its intended use. Corning 7980, and its predecessor Corning 7940, is formed in a refractory furnace[9] in which occasional high-index refractory dust particles are incorporated into the growing boule.[4] As shown schematically in Figure 4, these particles partially dissolve, forming a high-refractive index lenslet, which focuses the light and causes bulk damage immediately downstream at 351-nm fluences of 2-4 J/cm^2 (3 ns). Beam modulation continues to propagate to the rear surface, where a damage site appears. Material is preselected to eliminate visible inclusions, and the remaining inclusions are not visible until damage tested.

Figure 4. Schematic representation of the formation of bulk and rear surface damage from high index inclusions in some fused silicas. From Kozlowski et al.[4]



The number of inclusion-induced damage sites in Corning 7980 fused silica is typically a few dozen per 40-cm square aperture. With the remarkable recent advances in reducing polish-related damage sites and mitigating the growth of surface damage, these bulk inclusions would become the limiting factor for operating above 4 J/cm^2 (3 ns) at 351 nm. This is because no method has yet been developed to stop the reinitiation and growth of rear surface damage that they cause. Consequently, fused silicas manufactured without a surrounding refractory as in Figure 5 were pursued. 40-cm scale optics fabricated from Schott Lithosil Q and Heraeus Suprasil 312 were found to be free of inclusion-induced damage for exposure up to 14 J/cm^2 (3 ns) of 355-nm laser light.

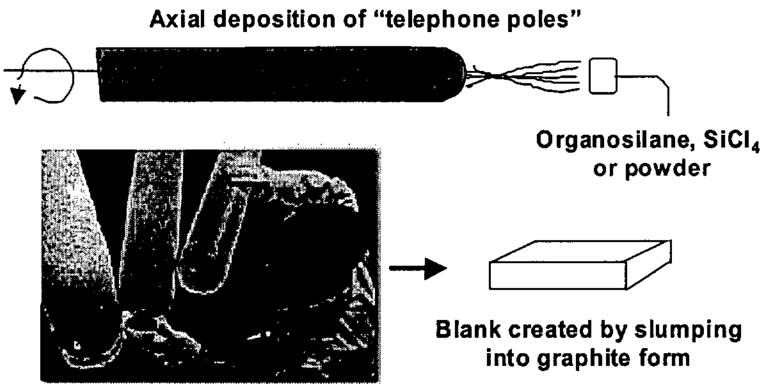


Figure 5. Formation of fused silica preforms by a method that eliminates bulk inclusions that can lead to laser-induced damage.

3.2 Crystals

KDP and DKDP can be grown either conventionally or rapidly. Conventional growth rates are about 1 mm/day, and it takes two years to grow a boule large enough for a 40-cm-scale optic. Pyramidal growth occurs from a plane seed, while prismatic growth is poisoned by trivalent impurities. Rapid growth occurs from a point seed in both the prismatic and pyramidal directions at a rate of about 10 mm/day and takes less than 2 months to grow a sufficiently large boule.

Unlike fused silica, bulk damage in KDP and DKDP is pervasive, forming thousands of damage pinpoints/mm^3 for fluences significantly above its bulk damage threshold. The pinpoint size depends on pulse length, ranging from a few μm at 1 ns to about 100 μm at 10 ns.[10] The pinpoints do not grow significantly, and their primary detriment is scattered light (scattered light fraction = f_s). Scattered light causes increased beam contrast, c, according to the relation $c = (2f_s)^{1/2}$,[11] increased stray light on the neighboring non-optical components, and a decrease in energy on target. Collateral damage from the first two far outweighs the third.

Attaining 351-nm damage-resistant DKDP has been the greater challenge and required three achievements: a quantitative relationship between routine bulk damage detection methods and scattered light levels, a method for reliably growing crystals with the required damage threshold, and a reliable method for conditioning the crystal prior to installation on the laser.

Four papers published last year provide the basis for first achievement. Damage measurements must be made on test coupons cut at the type-II tripler angle (59°C),[12] 0.1% scattered light levels correspond to ~10% damage probability,[10] obscuration increases exponentially with fluence and scales with pulse length to the 0.25 power,[10] and raster-scan laser conditioning can achieve damage resistance close to that inherent in the standard ramped fluence (R/1) damage test (Figure 6).[13] Using these results, a 10% R/1 damage probability fluence of 12.5 J/cm^2 (7.6 ns) for 355-nm light is estimated as the limit for materials to be operated at 8 J/cm^2 (3 ns) with a 15% beam contrast. Further, the relationship between fluence and scattering from bulk scattering, S, for an optimally conditioned crystals is estimated as

$$S(F) = 6.5\times10^{-6}\exp[11*F/F_0], \qquad (4)$$

Where F is the operating fluence at 3 ns and F_0 is the 10% damage probability fluence at 7.6 ns. Inserting Eq. (4) into Eq (3) gives the relationship between scattering after n shots and average fluence given in Table 2.

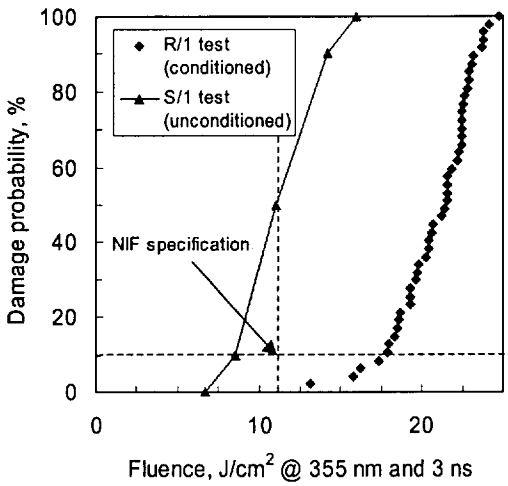


Figure 6. Standard small-beam bulk damage test results for conventional growth material 70%LL11, the first NIF production boule. The conditioned material (R/1 test) passes the NIF specification by a considerable margin. The S/1 test exposes each site to only a single fluence (no ramp).

Table 2. Calculated percentage of scattered light from bulk damage for a DKDP sample having a 10% R/1 damage probability of 12.5 J/cm^2 for a 3-ns 355-nm laser beam with 15% randomly migrating contrast. The material can tolerate a single shot at 10 J/cm^2 or at least 100 shots at 8 J/cm^2, since the random migration assumption is conservative. The shaded boxes represent the obscuration limit.

	Averagefluence, J/cm^2				
# shots	7	8	9	10	11
1	0.004	0.01	0.03	0.07	0.2
10	0.01	0.03	0.10	0.3	1.0
100	0.03	0.08	0.3	1.0	3.3
1000	0.05	0.18	0.7	2.5	9.1

The bulk damage precursors are thought to be absorbing nanoparticles.[14] Damage threshold improves with continuous filtration[15] and is lowered by addition of highly absorbing particulates such as iron phosphate (M. Yan, unpublished results, 1999). However, attempts to isolate and identify the specific precursors have been inconclusive, in part because of the low levels of material involved. One thousand 50-nm particles/mm^3 represent only ~0.1 ppb by weight of the crystal. Analysis methods attempted to date include ion milling into a damage site and analyzing it by time-of-flight SIMS, dissolving crystals and analyzing the collected particulate, and transmission electron microscopy (TEM).

In parallel, improvements to the growth procedures have largely solved the problem for both rapid and conventional growth. Satellite boules in NIF conventional growth production tanks yielded 10% R/1 damage values ranging from 12 to 17 J/cm^2, with an average of 14.5 J/cm^2. Three test samples from the first recovered production boule (Fig. 6) averaged 18 J/cm^2, suggesting that the satellite boules may underestimate quality. For rapid growth material, we reported last year that material rapidly grown below 45°C had a significantly higher damage resistance than material grown above 45°C.[16] However, work over the past year indicates that it is necessary to grow above 45°C to meet homogeneity requirements and to prevent crazing due to hydrogen exchange on the surface. Damage results for 20-L growth tanks are summarized in Figure 7. Similarly, samples across two large DKDP boules grown in 1200-L polycarbonate tanks have averaged 17.2 and 19.5 J/cm^2, respectively, for their 10% R/1 damage probability. The better material was grown exclusively above 45°C and slightly exceeds the best sample from a small tank boule at that temperature, indicating that scaleup is not a problem.

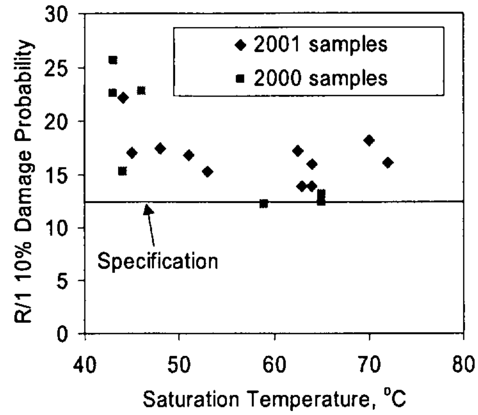


Figure 7. Summary of damage results for 20-L tank DKDP boules showing a general improvement over the past year for those grown above 45°C. About a 20°C temperature drop from the saturation temperature is required to grow a boule in this system. The improvement is thought to be due to a combination of improved salt purity and replacement of Pyrex tanks with polycarbonate tanks. Data include unpublished results of R. Floyd and T. Land (2001).

The final element in achieving high-fluence operation is offline conditioning, which allows an optic to be placed immediately into high-fluence operation. Last year we reported success in achieving R/1 damage performance for S/1 tests of DKDP that had been raster scanned by both 355-nm Nd-YAG and 308-nm XeCl excimer lasers.[13] The excimer laser conditioning parameters have been refined over the past year. Two significant results are the shift to a XeF laser at 351 nm to reduce induced absorption and the exceptional improvement of 1ω-damage resistance of KDP by conditioning at 351 nm.[17]

4. REDUCING SURFACE DAMAGE INITIATION

4.1 Fused Silica

Fused silica is an inherently good material with respect to surface damage, but flaws induced during finishing have typically lowered the damage resistance to a small fraction of the dielectric breakdown limit. In order to improve fused silica 351-nm lifetimes significantly, we explored in parallel the basic mechanisms of laser-induced surface damage, pursued improvements in conventional finishing, and explored advanced finishing concepts. A summary of that effort is given in Table 3. While the scientific efforts helped refine our understanding of the damage process, a combination of magneto-rheological finishing followed by acid etching and 3ω laser conditioning was most successful at solving the problem.

Table 3. Outline of effort over the past two years to improve the surface damage initiation. Scientific and engineering approaches were pursued in parallel.

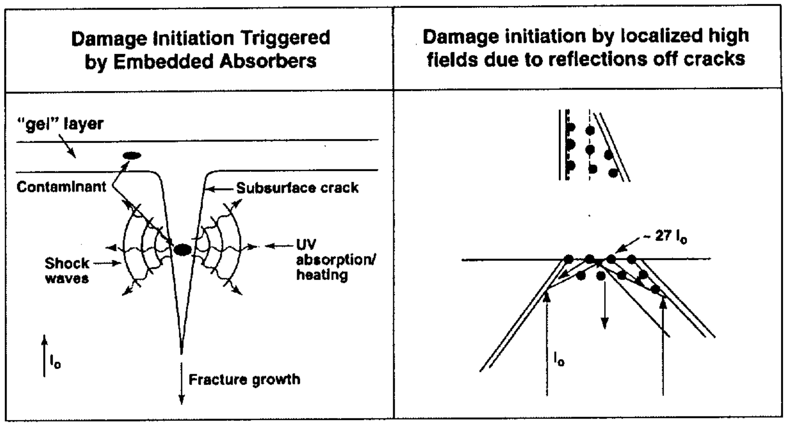
- Fundamental studies to understand the mechanism of initiation
  - Argonne LIMS of engineered defects
  - TEM characterization of pilot-production optics
  - Spectroscopic evaluation of damage craters

- Engineering approaches to improved finishing
  - Acid etch to completely remove subsurface damage
  - 3w laser conditioning
  - Repolish after damage initiation
  - Magneto-rheological finishing
  - CO_2 laser polishing
  - Surface reflow by ion implantation
  - Surface removal by plasma etching

Increasing difficulty of implementation

It has been known for some time that surface damage is caused by some combination of subsurface cracks and imbedded contamination,[18] and possible mechanisms are summarized in Figure 8. Damage can be caused by absorbing particulates in either the redeposition ("gel") layer or subsurface cracks from grinding and polishing. Recent experiments at both the University of Rochester and at LLNL find that gold nanoparticles overcoated with a high-quality silica layer damage below 10 J/cm^2 at 355 nm.[19,20] Also, nanoparticles of carbon and brass have been found by TEM in the subsurface of a high-quality optic polished by a potential vendor.[21] However, contamination is not required, since both fractured surfaces and clean scratches and indents also damage below 10 J/cm^2,[22] and the damage fluence depends on the amount of mechanically induced brittle fracture.[20]

Figure 8. Schematic diagram of damage initiation mechanisms. The left shows damage initiated by absorbing particulates either in the redeposition ("gel") layer or in cracks, and the right shows damage initiated by field enhancement to constructive interference of light reflected by cracks.



The classic example of surface damage from contaminants in the redeposition layer is the appearance of gray haze, which is thought to occur from residual ceria particles used in the polishing process.[23,24] This damage mechanism can be eliminated by either use of zirconia in the final polishing steps or by acid etching. This leaves either cracks or contamination in cracks as potential damage mechanisms. Even though most subsurface damage does not lead to surface damage at fluences relevant to operation of large aperture lasers, eliminating cracks would also eliminate the associated contamination, thereby solving the problem regardless of its precise origin. Also, the remaining issue is one of large-area damage density, since even one damage site at high fluence will rapidly destroy an optic.

CO_2 annealing of the surface has been reported to increase 1064-nm damage resistance by reducing the amount of subsurface damage as detected by total internal reflection microscopy.[25] Although our initial efforts also showed a ~10 J/cm^2 increase in the R/1 damage profile, further work was unsuccessful at finding conditions that would maintain transmitted wavefront quality.[26] Consequently, large-aperture damage density measurements were not attempted. Similarly, a high-temperature plasma removal process achieved minor increases in the R/1 damage profile, but thermally induced stress and wavefront issues were not resolved with the modest effort applied. Never the less, the partial success of the CO_2 treatment confirmed that further reduction of subsurface damage during polishing would reduce damage densities.

Another approach was to etch away the subsurface damage by a low-temperature method that would not involve material reflow. However, etching with neither HF/NH_4F nor a low-temperature plasma torch showed significant benefit. Both tended to convert existing subsurface damage into increased microroughness when present, although the increase is negligible for high-quality optics. The acid etch technique was explored more completely. However, even when 100-200 μm of material was removed, no significant reduction in damage densities was achieved. Our presumption is that subsurface cracks tend to run ahead of the etching processes.

Although laser conditioning is routinely used to improve damage resistance of many optics,[27] and there is one report of conditioning at 248 nm,[28] it was generally thought not to be effective for improving damage resistance at 351 nm, The conclusion of no conditioning may be based on the fact that the S/1 and R/1 curves for fused silica, unlike crystals as seen in Figure 6, are basically within experimental precision. However, the principal concern for large aperture lasers is the low fluence (<14 J/cm^2 at 3 ns), large-area damage densities rather than the high-fluence (>25 J/cm^2), small-area damage probabilities measured by an R/1 test. It is quite important, therefore, that a significant reduction—typically fourfold—in the low fluence damage densities has been observed repeatedly for high-quality polished optics.[29]

Finally, samples finished by magneto-rheological finishing were supplied by Zygo Corporation. As received, the samples had very poor damage performance. However, when residual iron and ceria from the polishing process were removed by acid etching and residual initiators were reduced by 355-nm laser conditioning, a nearly complete elimination of damage below 10 J/cm^2 and a nearly 100-fold reduction at 14 J/cm^2 were obtained.[30] The overall progress in damage reduction over the past years is summarized in Figure 9. This last improvement makes practical the mitigation of the pre-initiated damage sites, as outlined in a later section.

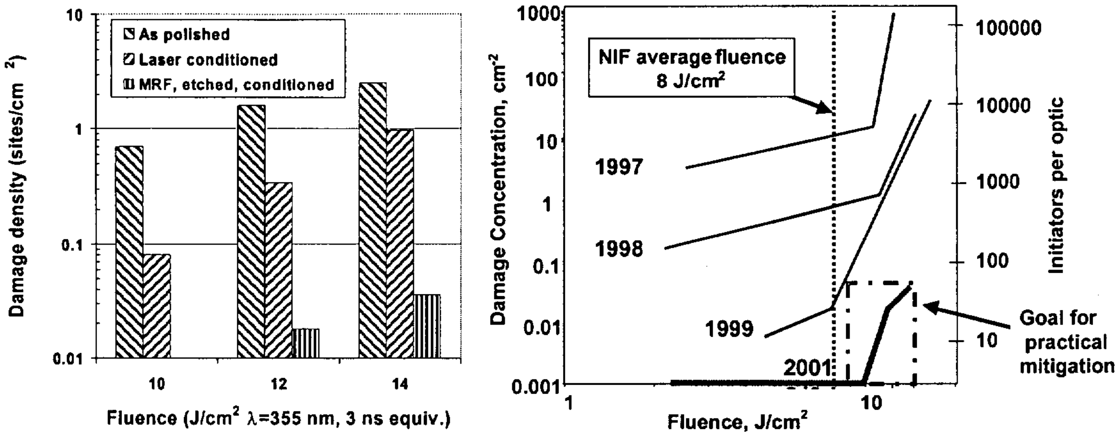


Figure 9. Progressive reduction of initiators in fused silica optics through process improvements. The low damage density values achieved in 2001 were due to a combination of magneto-rheological finishing, acid-etching, and laser conditioning, as seen on the left-hand figure. Earlier improvements were due to improved management of subsurface damage and elimination of ceria from the final polishing steps. The 1999 data on the right are similar to the "as polished" damage densities on the left, which represent the current state of the art for lenses without MRF.

4.2 DKDP

Surface damage initiation for DKDP is less well understood than for fused silica. Large aperture conversion crystals were operated in air on Beamlet at an average fluence of 8 J/cm^2 with no apparent surface damage.[31] Surface damage was present on some later Beamlet experiments, but it was not clear whether it was due to fabrication defects, the vacuum environment, or tighter optics spacing. As a result, we embarked on a program to identify defects leading to surface damage on crystals, which is described in detail by Demos et al.[32]

A central feature in this effort was the creation of scattering and flourescence mapping facilities with a resolution on the scale of a few micrometers that can scan and record images of crystals prior to damage testing. Although this work is still in its early stages, a correlation has emerged between the presence of elongated fluorescent bodies and surface damage. The origin and composition of these defects is currently under investigation.

5. MITIGATION OF SURFACE DAMAGE GROWTH

Surface damage initiation would not be a serious problem if the damage did not grow. For example, 1000 damage sites 50 µm in diameter over a 1000-cm^2 clear aperture cover less than 0.01% of the area. However, surface damage grows exponentially in area above a threshold fluence. The threshold fluence is known fairly well for fused silica and is 5.5 ± 0.5 J/cm^2, independent of pulse length to within experimental precision for pulse lengths in the 1-10 ns range.[2] The threshold seems to be more variable for DKDP, though it is usually higher than for fused silica. Also, DKDP sometimes shows a transition from slow to rapid crater growth.

Surface damage growth requires an absorption mechanism to supply energy for the absorption. For both SiO_2 and DKDP, damage craters show UV-induced fluorescence. Upon exposure to >2 J/cm^2 of UV laser light, localized plasmas are formed and merge into continuous plasma across the damage crater at a fluence approximately equal to the damage growth threshold.[33] By eliminating the absorption source, damage growth could be stopped. A variety of approaches were pursued, which are described in more detail for fused silica in the following paragraphs. The corresponding effort for DKDP is at an earlier stage and will be reported later.

Parallel investigations for fused silica pursued a basic understanding of the damage characteristics causing absorption and methods to eliminate either the absorption or its effect on growth. A combination of x-ray tomography,[34] Raman spectroscopy,[35] and UV-induced fluorescence studies[36] showed previously that about 10 µm of the fused silica in the bottom of the damage crater is densified, thereby forming a variety of absorbing defects without changing the overall stoichiometry of the material. Modeling this year confirmed that the densification and enhanced absorption is a direct result of the shock wave formed by the damage event.[37,38] Although a detailed model of the damage growth process has not been developed, it is also clear that the surrounding crack network both weakens the surrounding material as well as provides the opportunity for additional absorption due to locally enhanced intensity due reflections and scattering.[22]

Consequently, it is clear that damage growth can be stopped only by either removing or remelting the damaged material. An initial attempt at removing the damaged material by whole surface HF etching was reported last year;[39] this method was only partially successful. During the past year, localized surface removal and modification methods were explored, including acid etching, plasma etching, and CO_2 laser treatment.[40] The latter was the most successful, as well as the easiest to implement.[41] An important result reported in this proceedings showed that only local melting, not ablation, is needed to stop damage growth on large damage sites formed at 45 J/cm^2 (355 nm, 8 ns) for subsequent exposure up to 14 J/cm^2 (10 ns). Very recent work has improved the process so that smaller damage sites initiated at 355-nm fluences up to 14 J/cm^2 (3 ns) can survive subsequent exposure to 14 J/cm^2 (3 ns) (W. Molander, unpublished results, 2001).

An alternate approach of stopping or slowing damage was also explored and is reported here for completeness. It was hypothesized that variations in trace species, such as water or fluorine, in the fused silica might alter its susceptibility to damage growth, either through changes in the propensity to form absorbing defects or by slight changes in mechanical properties. Various specialty grades of fused silica were acquired and polished by a standard process. Damage was then initiated at 45 J/cm^2 (7.6 ns) and exposed to fluences up to 12 J/cm^2 (11 ns). As shown in Figure 10, however, there is no difference in damage growth for any of these materials, confirming that the factors leading to damage growth are intrinsic to fused silica.

6. UV VACUUM EFFECTS

Previous work showed that the surfaces of both fused silica and DKDP degrade upon prolonged exposure to 355-nm laser light.[5,6] For fused silica, a thin layer of sub-stoichiometric SiOx is formed, which absorbs some of the 355-nm light and fluoresces in the visible and IR. Operational experience for the spatial filters of the Optical Science and Slab Lab lasers has found that only a few millitorr of air are required to prevent its formation. Similarly, 10 Torr of air eliminates an observed increase in surface crater damage.[5]

During the past year, the effect of gas pressure on UV-induced surface degradation was explored in more detail for DKDP.[42] DKDP shows two deleterious effects—absorption-fluorescence and roughening-scattering. Although neither are understood in any detail, both can be eliminated by the presence of gas, either air or nitrogen, at the 1-10 Torr level. As a result, the debris shield seal in the NIF final optics assembly was modified so that the final optics can operate at 10 Torr, thereby eliminating the potentially deleterious effects of vacuum.

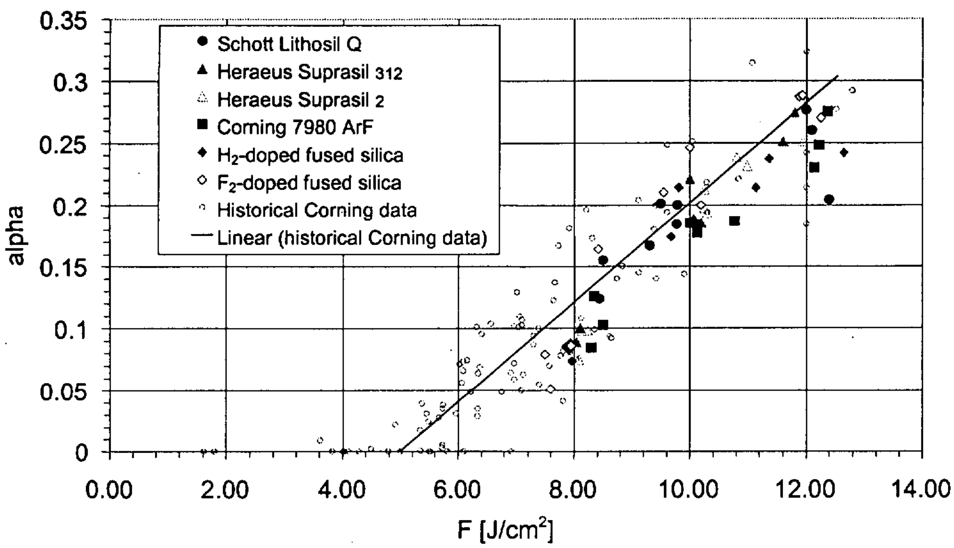


Figure 10. Surface damage growth rates for various commercial grades of fused silica. Growth is governed by the relation $L = L_0 e^{\alpha N}$, where L is the diameter of the damage crater, N is the number of shots, and α is the growth coefficient. Subtle changes in composition have no detectable affect on growth.

7. OPERATIONAL STRATEGY FOR THE NIF FINAL OPTICS

With these advances in both understanding and control of laser-induced damage, an improved operational strategy for the NIF final optics was devised. The basic elements are given in Figure 2, and an expanded view of the post-processing/recycling aspects is given in Figure 11. The basic concept is to precondition any optic susceptible to damage, pre-initiate and mitigate any surface damage, establish environmental conditions that minimize damage during operations (see preceding section), and then retrieve and repair optics damaged during operations.

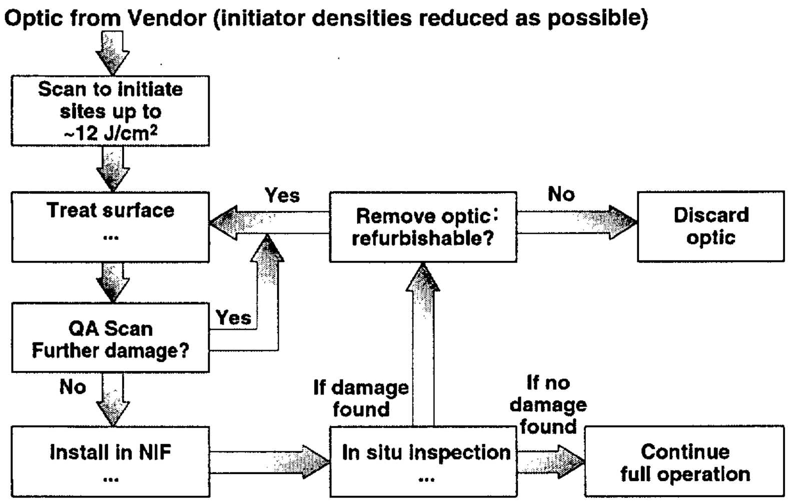


Figure 11. Schematic diagram of the final optics post-processing and recycling scheme.

One of the main issues to be considered for optics lifetime predictions for this strategy is the effect of beam contrast during both post-processing and subsequent operation. The mitigation process is shown schematically in Figure 12 for a surface damage density distribution from an MRF-polished part. The presence of beam contrast means that there is no sharp cut-off fluence for which surface damage sites have and have not been initiated. Multiple passes with a migrating contrast increase the mean exposure fluence and narrow the distribution, as shown in Figure 3. For this particular example, 5 passes at 12 J/cm^2 with a beam having a 15% contrast, effectively pre-initiates all sites below 11 J/cm^2 and initiates few above 15 J/cm^2. This corresponds to about 50 damage sites for an MRF-polished part.

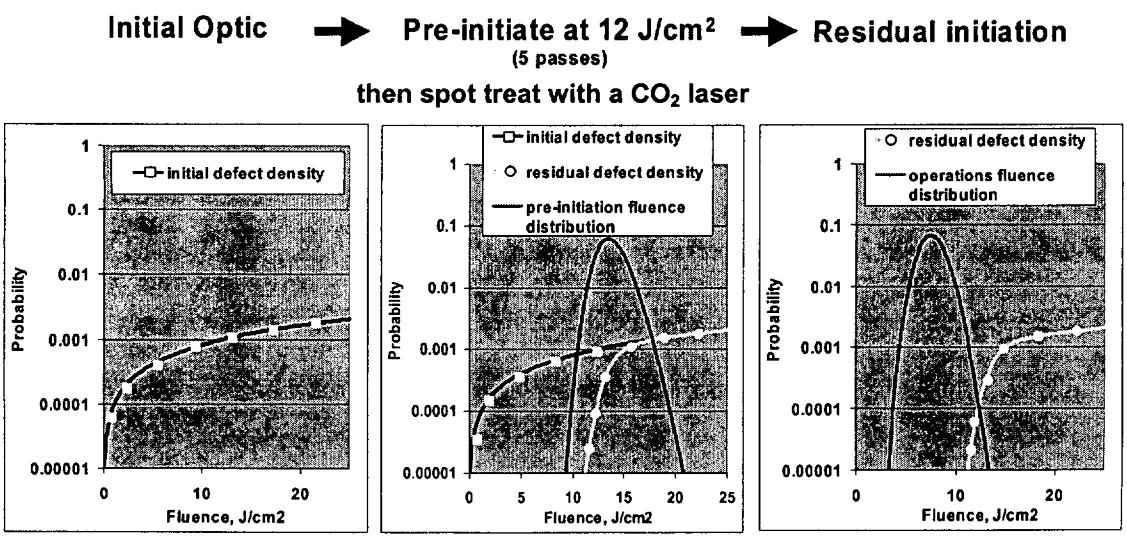


Figure 12. Schematic representation of the mitigation process statistics for an MRF part. Damage sites at the low end of the beam fluence distribution are not fully initiated, while others are initiated at the high end of the fluence distribution that would not initiated on line.

After installation, there is a finite probability that a residual defect is exposed to a high fluence portion of the beam. Using Equations (1) and (3), one finds that it takes on average ~7600 shots at 8 J/cm^2 with 15% beam contrast for a hot spot in the beam to find a residual defect. (This is probably an overestimate of the lifetime due to the potential presence of contamination induced damage.) Once initiation has occurred, the damage site grows to unacceptable size in tens of shots at 8 J/cm^2. Consequently, the optic must be retrieved and repaired promptly. To accomplish this, the conversion crystals and final focus lens are now held in a line-replaceable cassette, enabling rapid retrieval, repair, and replacement upon damage detection.

SUMMARY

A combination of fundamental science and engineering improvements have led to greatly improved damage performance of large-aperture UV optics such as those to be used on the National Ignition Facility. Elimination of bulk inclusions in fused silica and improvements in KDP growth and laser conditioning processes has essentially eliminated those mechanisms for operation at an average fluence of 8 J/cm^2, and modification of the final optics assembly to operate at 10 Torr eliminates vacuum-enhanced surface degradation mechanisms. Advances in fused silica finishing have greatly reduced the subsurface damage and reduced surface contamination, resulting in only ~50 surface damage initiation sites for 40-cm scale optics. Pre-initiating these sites offline and spot treating them with a CO_2 laser eliminates the formation and growth of these sites online. Progress has also been made on understanding the origin of surface damage on crystals. These advances have been combined into a new concept of pre-initiating and repairing damage prior to installation, then frequently inspecting the optics during operations to retrieve and repair the optics prior to development of unacceptable levels of damage. This process not only allows the optics to be recycled several times but also reduces the collateral damage on neighboring optics.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. The contributions of many other individuals to the various tasks summarized here is greatly appreciated, including Chris Adams, Ray Brusasco, Jeff Carr, Gene Donohue, Randy Floyd, Ruth Hawley-Fedder, Terry Land, Jim McElroy, Bill Molander, Kurt Neeb, Mike Nichols, Mary Norton, John Peterson, Wally Sell, Dave Swift, and Tim Weiland.

REFERENCES

1. J. R. Murray, "Overview of the National Ignition Facility," *Third Annual Intl Conf. of Solid State Lasers for Application to ICF*, Suppl. to Proceedings of SPIE, Vol. 3492, pp. 1-10 (1998).
2. M. Norton, L. Hrubesh, Z. Wu, M. Feit, M. Kozlowski, D. Milam, K. Neeb, W. Molander, A. Rubenchik, W. Sell, P. Wegner, "Growth of laser-initiated damage in fused silica at 351 nm," *Laser Science and Technology Program Annual Report—2000*, LLNL Report UCRL-ID-142744-00 and UCRL-JC-13964 (2001).
3. M. Runkel, J. De Yoreo, W. Sell, D. Milam, "Laser conditioning study of KDP on the Optical Sciences Laser using large area beams," *Laser-Induced Damage in Optical Materials: 1997*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3244, pp. 51-63 (1998).
4. M. R. Kozlowski, R. Mouser, S. Maricle, P. Wegner, and T. Weiland, "Laser damage performance of fused silica optical components measured on the Beamlet laser at 351 nm," *Laser-Induced Damage in Optical Materials: 1998*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3578, pp. 436-443 (1999).
5. A.K. Burnham, M. Runkel, S. G. Demos, M. R. Kozlowski, P. J. Wegner "Effect of vacuum on the occurrence of UV-induced surface photoluminescence, transmission loss, and catastrophic surface damage," *Photonics for Space Environments VII*, E. W. Taylor, ed., Proceedings of SPIE, Vol. 4134, pp. 243-252, (2000).
6. S. G. Demos, A. Burnham, P. Wegner, M. Norton, L. Zeller, M. Runkel, M. R. Kozlowski, M. Staggs, H. B. Radousky, "Surface defect generation in optical materials under high fluence laser irradiation in vacuum," *Electronic Lett.* **36**, 566-567 (2000).
7. M. D. Feit, A. M. Rubenchik, M. R. Kozlowski, F. Y. Genin, S. Schwartz, L. M. Sheehan, "Extrapolation of damage test data to predict performance of large-area NIF optics at 355 nm," *Laser-Induced Damage in Optical Materials: 1998*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3578, pp. 226-233 (1999).
8. P. Wegner and M. Henessian, "Mathematical model for describing the intensity statistics of ICF laser beams," LLNL internal memorandum, 1990.
9. M. S. Dobbins, R. E. McLay, "Method of making fused silica by decomposing siloxanes," U.S. Patent 5,043,002, August 27, 1991.

10. M. Runkel, A. Burnham, D. Milam, W. Sell, M. Feit, A. Rubenchik, "The results of pulse-scaling experiments on rapid-growth DKDP triplers using the Optical Sciences Laser at 351 nm," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, pp. 359-368 (2001).
11. J. W. Goodman, "Statistical properties of laser speckle patterns," *Laser Speckle and Related Phenomena, Topics in Applied Physics, Vol 9*, J. C. Dainty, ed., Springer-Verlag, Berlin, 1975, p. 31.
12. M. Runkel and A. Burnham, "Differences in bulk damage probability distributions between tripler and z-cuts of KDP and DKDP at 355 nm," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 408-419 (2001).
13. M. Staggs, M. Yan, M. Runkel, "Laser raster conditioning of KDP and DKDP crystals using XeCl and Nd:YAG lasers," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., *Proceedings of SPIE, Vol. 4347*, 400-407 (2001).
14. M. D. Feit, A. M. Rubenchik, M. Runkel, "Analysis of bulk DKDP damage distribution, obscuration and pulse length dependence," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 383-388 (2001).
15. N. Zaitseva, J. Atherton, R. Rozsa, L. Carman, I. Smolsky, M. Runkel, R. Ryon, L. James, "Design and benefits of continuous filtration in rapid growth of large KDP and DKDP crystals," *J. Crystal Growth* **197**, 911-920 (1999).
16. A. K. Burnham, M.Runkel, R. Hawley-Fedder, L. Carman, R. Torres, P. Whitman, "Low-temperature growth of DKDP for improved 3ω-damage resistance," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 373-381 (2001).
17. M. Runkel, K. Neeb, M. Staggs, J. Auerbach, A. Burnham, "Raster-scan laser conditioning studies on frequency conversion crystals using Nd:YAG and excimer lasers," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
18. L. Sheehan, M. Kozlowski, D. W. Camp, "Application of total internal reflection microscopy for laser damage studies on fused silica," *Laser-Induced Damage in Optical Materials: 1997*, G. J. Exarhos, ed., *Proceedings of SPIE, Vol. 3244*, 282-295 (1998).
19. S. Papernov, A. W. Schmid, R. Krishnan, L. Tsybesdov, "Using colloidal gold nanoparticles for studies of laser interaction with defects in thin films," *Laser-Induced Damage in Optical Materials: 2000*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 146-154 (2001).
20. A. V. Hamza, W. J. Seikhaus, A. M. Rubenchik, M. Feit, L. L. Chase, M. Savina, M. J. Pellin, I. D. Hutcheon, M. C. Nostrand, M. Runkel, B. W. Choi, M. Staggs, and M. J. Fluss, "Engineered defects for investigation of laser-induced damage of fused silica at 355nm," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
21. Fluss et al, *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
22. F. Y. Génin, A. Salleo, T. V. Pistor, L. L. Chase, Role of light intensification by cracks in optical breakdown on surfaces," *J. Opt. Soc. Am. A* **18**, 2607-2616 (2001).
23. M. R. Kozlowski, J. Carr, I. Hutcheon, R. Torres, L. Sheehan, D. Camp, M. Yan, "Depth profiling of polishing-induced contamination on fused silica surfaces," *Laser-Induced Damage in Optical Materials: 1997*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3244, 365-375 (1998).
24. C. L. Battersby, L. M. Sheehan, M. R. Kozlowski, "Effects of wet etch processing on Laser-induced damage of fused silica surfaces," *Laser-Induced Damage in Optical Materials: 1998*, G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3578, 446-455 (1999).
25. P. A. Temple, D. Milam, and W. H. Lowdermilk, "CO_2-laser polishing of fused silica surfaces for increased laser damage resistance at 1.06 μm," *Damage in Laser Materials: 1979*, H. E. Bennett, ed., Nat. Bur. Stand. (U.S.) Spec. Publ. 568, pp. 229-236 (1979).
26. R. M. Brusasco, B. M. Penetrante, J. A. Butler, S. M. Maricle, J. E. Peterson, "CO_2-laser polishing for reduction of 351-nm surface damage initiation in fused silica," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
27. F. Rainer, R. M. Brusasco, J. H. Campbell, F. P. DeMarco, R. P. Gonzales, M. R. Kozlowski, F. P. Milanovich, A. J. Morgan, M. S. Scrivener, M. C. Staggs, I. M. Thomas, S. P. Velsco, C. R. Wolfe, "Damage measurements on optical materials for use in high-peak-power lasers," *Laser-Induced Damage in Optical Materials: 1989*, H. E. Bennett, ed., NIST Special Publication 801, pp. 74-83 (1990).
[28] N. C. Kerr and D. C. Emmony, "The effect of laser annealing of laser induced damage threshold," *Laser-Induced Damage in Optical Materials: 1989*, H. E. Bennett, ed., *NIST Special Publication 801*, pp. 164-179 (1990).
29. R. M. Brusasco, B. M. Penetrante, J. E. Peterson, S. M. Maricle, J. A. Menapace, "UV-laser conditioning for reduction of 351-nm damage initiation in fused silica," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
30. J. A. Menapace, B. Penetrante, D. Golini, A. Slomba, P. E. Miller, T. Parham, M. Nichols, and J. Peterson, "Combined Advanced Finishing and UV Laser Conditioning for Producing UV Damage Resistant Fused Silica Optics," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.

31. B. M. Van Wonterghem, J. R. Murray, J. H. Campbell, D. R. Speck, C. E. Barker, I. C. Smith, D. F. Browning, W. C. Behrendt, "Performance of a prototype for a large-aperture multipass Nd:glass laser for inertial confinement fusion," *Applied Optics* **36**, 4932-4953.
32. S. G. Demos, M. Nostrand, M. Staggs, C.W. Carr, D. Hahn, A. Burnham," Investigation of fluorescence imaging as a tool for noninvasive detection and imaging of damage precursors at 3ω," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
33. S. G. Demos, M. R. Kozlowski, M. Staggs, L. L. Chase, A. Burnham, H. B. Radousky, "Mechanisms to explain damage growth in optical materials," *Laser-Induced Damage in Optical Materials: 2000,* G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 277-282 (2001).
34. J. Wong, D. Haupt, J. H. Kinney, M. Stevens-Kalceff, A. Stesmans, J. Ferreira, E. Lindsey, and I. Hutcheon, *Morphology, Microstructure and Defects in Fused Silica Induced by High-Power 355-nm Laser Pulses*, Lawrence Livermore National Laboratory Report UCRL-JC-142167 (2001).
35. S. G. Demos, L. Sheehan, M. R. Kozlowski, "Spectroscopic investigation of SiO2 surfaces of optical materials for high-power lasers," *Laser Applications in Microelectronic and Optoelectronic Manufacturing V*, H. Helvajian, ed., *Proceedings of SPIE, Vol. 3933*, pp. 316-321 (2000).
36. M. R. Kozlowski, C. L. Battersby, S. G. Demos, "Luminescence investigation of SiO2 surfaces damaged by 0.35 μm laser illumination," *Laser-Induced Damage in Optical Materials: 1999,* G. J. Exarhos, ed., Proceedings of SPIE, Vol. 3902, 138-143 (2000).
37. A. Kubota, M. J. Caturla, J. S. Stolken, M.D. Feit, "Densification of fused silica due to shock waves and its implications for 351-nm laser-induced damage," *Optics Express* **8**, 611-616 (2001)
38. A. Kubota, L. Davila, M.J. Caturla, J. S. Stolken, B. Sadigh, A. Quong, A. Rubinchek, M. D. Feit, "Structural modifications in fused silica due to laser damage induced shock compression," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
39. L. W. Hrubesh, M. A. Norton, W. A. Molander, P. J. Wegner, M. Staggs, S. G. Demos, J. A. Britten, L. J. Summers, E. F. Linsey, M. R. Kozlowski, "Chemical etch effects on laser-induced surface damage growth in fused silica," *Laser-Induced Damage in Optical Materials: 2000,* G. J. Exarhos, ed., Proceedings of SPIE, Vol. 4347, 553-559 (2001).
40. L. W.Hrubesh, M. A.Norton, W. A.Molander, E. E.Donohue, S. M.Maricle, B. M.Penetrante, R. M.Brusasco, W.Grundler, J. A.Butler, J. W.Carr, R. M.Hill, L. J.Summers, M. D.Feit, A.Rubenchik, M. H.Key, P. J.Wegner, A. K.Burnham, L. A. Hackel, M. R.Kozlowski, "Methods for mitigating surface damage growth on NIF final optics," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
41. R. M. Brusasco, B. M. Penetrante, J. A. Butler, L. W. Hrubesh, "Localised CO_2-laser treatment for mitigation of 351-nm damage growth on fused silica," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.
42. P. Whitman, M. Norton, M. Nostrand, W. Molander, A. Nelson, M. Engelhard, D. Gaspar, D. Baer, W. Siekhaus, J. Auerbach, S. Demos, M. Staggs, A. Burnham, "Degradation of bare and sol-gel coated DKDP crystals exposed to multiple 351-nm laser pulses," *Laser-Induced Damage in Optical Materials: 2001*, this proceedings.